COMPATIBILITY OF THE RADIO FREQUENCY MASS GAUGE WITH GRAPHITE-EPOXY COMPOSITE TANKS

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ABSTRACT

The radio frequency mass gauge (RFMG) is a low-gravity propellant quantity gauge being developed at NASA for possible use in long-duration space missions utilizing cryogenic propellants. As part of the RFMG technology development process, we evaluated the compatibility of the RFMG with a graphite-epoxy composite material used to construct propellant tanks. The key material property that can affect compatibility with the RFMG is the electrical conductivity. Using samples of 8552/IM7 graphite-epoxy composite, we characterized the resistivity and reflectivity over a range of frequencies. An RF impedance analyzer was used to characterize the out-of-plane electrical properties (along the sample thickness) in the frequency range 10 to 1800 MHZ. The resistivity value at 500 MHz was 4.8 ohm-cm. Microwave waveguide measurements of samples in the range 1.7 – 2.6 GHz, performed by inserting the samples into a WR-430 waveguide, showed reflectivity values above 98%. Together, these results suggested that a tank constructed from graphite/epoxy composite would produce good quality electromagnetic tank modes, which is needed for the RFMG. This was verified by room-temperature measurements of the electromagnetic modes of a 2.4 m diameter tank constructed by Boeing from similar graphite-epoxy composite material. The quality factor Q of the tank electromagnetic modes, measured via RF reflection measurements from an antenna mounted in the tank, was typically in the range $400 < Q < 3000$. The good quality modes observed in the tank indicate that the RFMG is compatible with graphite-epoxy tanks, and thus the RFMG could be used as a low-gravity propellant quantity gauge in such tanks filled with cryogenic propellants.

INTRODUCTION

Long duration spaceflight missions with large payload capabilities will require the development of many new technologies such as those outlined in NASA's Space Technology Roadmaps [1]. High energy cryogenic propellants, such as liquid hydrogen and liquid oxygen, will almost certainly be part of the in-space propulsion systems for such missions. One of the cryogenic propellant management technologies being developed by NASA is a low-gravity propellant quantity gauge known as the Radio Frequency Mass Gauge (RFMG) [2, 3]. A low-gravity propellant gauge would offer the benefit of not having to provide a settling thrust in order to gauge the propellant tanks, thus saving propellant resources.

The RFMG operates by measuring the natural electromagnetic eigenmode frequencies of a tank, and comparing these frequencies with a database of RF simulations of the tank containing various fluid fill levels and liquid configurations. Because the liquid slows the speed of electromagnetic waves in a known way, the changes to the electromagnetic modes of the tank can be computed a-priori and those simulations are used to compare with the measured tank spectrum. A best match between the measured tank mode frequencies and the computed tank mode frequencies occurs at some fill level which is then reported as the gauged liquid level in the tank.

Ground-based testing of the RFMG has shown that propellant gauging uncertainties as low as 1% of full scale can be achieved when there is a very good match between the computed and measured tank modes before any propellant is introduced, indicating a good match between the high-fidelity tank model and the actual tank dimensions. Figure 1 shows the RFMG measurement principle and an

example spectra from a 1.4 m diameter aluminum tank that was used for liquid hydrogen testing. The tank contained a temperature/level sensor rake that was also included in the RF model. As can be seen, there is excellent agreement between the RF simulations and the measured spectra. The addition of cryogenic propellant to the tank changes the electromagnetic modes in a predictable way since the liquid slows the speed of light an amount depending on the index of refraction of the liquid. The frequency shift of a given mode also depends on the distribution of liquid inside the tank, which cannot necessarily be predicted in advance so that several thousand simulations at various fill levels and liquid configurations may be needed as part of the database for a low-gravity application. Nevertheless, for a given tank geometry and liquid configuration these changes can be accurately predicted with RF simulations software and form the basis of the RFMG.

As part of the RFMG technology development effort we have conducted 1g testing with liquid hydrogen, oxygen and methane, and low-gravity aircraft testing with a room temperature simulant fluid. All of those tests were conducted with metal tanks, which provides excellent RF reflectivity and creates high quality factor (Q) modes in the tank. The measured Q factor of a mode is defined by the ratio of mode frequency to the full width at half-maxima in the power spectrum, $Q = f/\Delta f$. The Q-factor depends on the relative magnetic permeability of the tank walls μ_c/μ, the skin depth δ, the volume to surface area ratio, and a geometrical factor which is of order unity [4]:

$$Q = \frac{\mu}{\mu_c}\left(\frac{V}{S\delta}\right) \times (Geometrical\ factor) \qquad (1)$$

where V and S are the tank volume and surface area respectively, and the skin depth is given by $\delta = [2/(\mu_c\omega\sigma)]^{1/2}$ where ω is the angular frequency and σ is the electrical conductivity. For metal tanks, such as stainless steel or aluminum, the Q-factor can easily range from 10^3 – 10^5 or higher depending on the size of the tank and material. Very high Q values (such as 10^5) can make spectrum measurements more difficult since a very fine frequency step resolution is needed during the measurement in order to fully resolve the peaks in the spectrum.

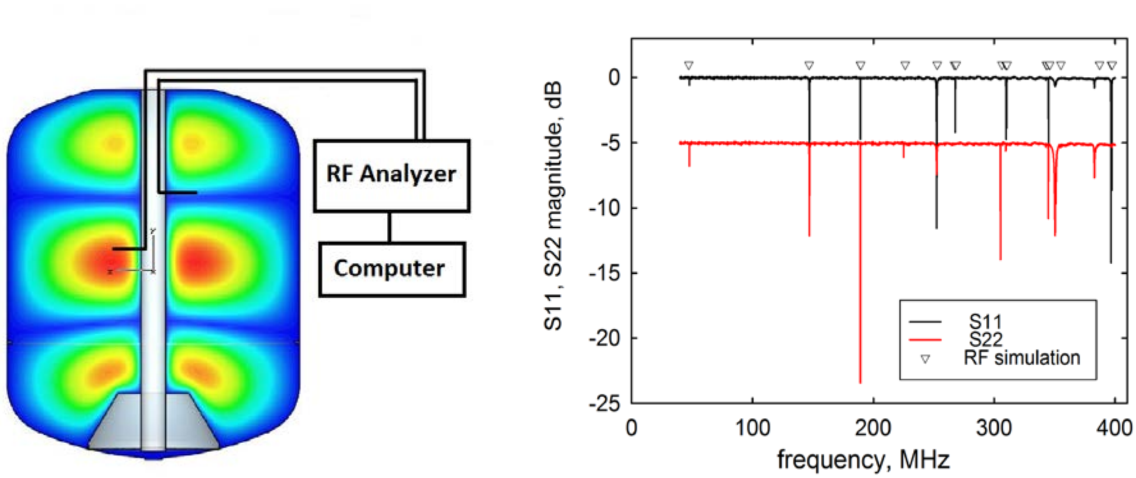


Figure 1. Schematic representation of the RFMG measurement system (left) and sample spectra from a 1.4 m diameter aluminum tank (right) showing the magnitude of s-parameters S11 and S22 measured from two antennas inside the tank. The S22 spectrum has been offset by –5 dB for clarity.

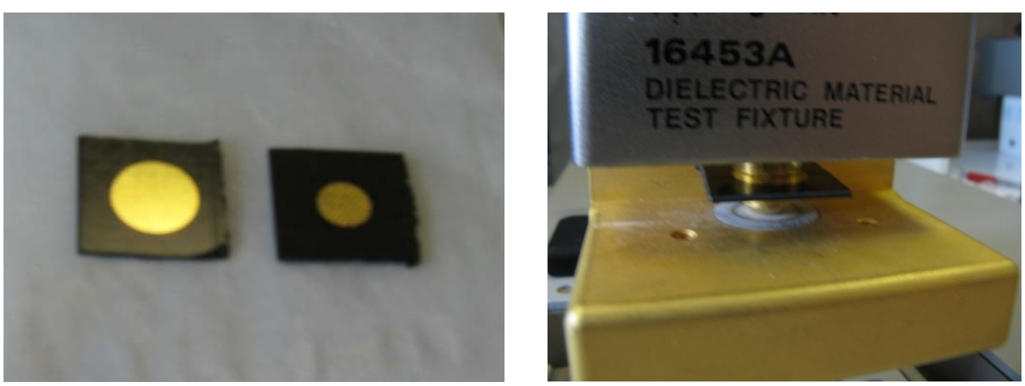
A risk that was identified in the RFMG development effort was the effect of a composite tank, such as a graphite-epoxy material, on the quality factor of the RF tank modes. Composite cryogenic tanks are a promising technology that will help reduce the dry mass of a stage, leading to higher performance propulsion stages. Carbon composite materials have anisotropic electrical conductivity and it was conjectured that the anisotropic nature of the composite material and complex surface currents inside the tank would have an unknown effect on the tank RF spectra. The in-plane (parallel to the plate surface) conductivity is typically higher than the out-of-plane conductivity (through the plate thickness) because the carbon fiber mesh intrinsically has low resistivity, and sequential mesh layers are overlaid and joined using a resin with lower conductivity. Epoxy, which is an electrical insulator, is often used as the resin material. The electrical resistivity through the thickness of carbon fiber composites typically ranges from 10 – 1,000 ohm-cm, whereas the in-plane resistivity is as low as 2.5×10^{-3} ohm-cm [5]. In order to address the concern regarding the RFMG compatibility with composite tanks, we obtained samples of an 8552/IM7 graphite-epoxy composite and used them to conduct preliminary RF electrical characterization tests, and also obtained RF spectrum measurements from a 2.4 m diameter composite tank manufactured by Boeing.

RESULTS AND DISCUSSION

We conducted RF electrical characterization tests of 8552/IM7 graphite-epoxy samples using an RF impedance analyzer and waveguide measurements. Panels of the composite material, 0.91m x 0.91m, were used to construct a box for preliminary RF mode testing and EMI/EMC characterization. Finally, we show RF mode testing of a 2.4 m diameter composite tank manufactured by Boeing and delivered to NASA.

RF IMPEDANCE ANALYZER MEASUREMENTS

Resistivity measurements for carbon composite fiber materials similar to those used for the RFMG chamber were measured from 10 MHz - 100 MHz using an Agilent 4291B RF impedance analyzer [6]. Gold electrodes were applied to test coupons of the16-ply, 0.096 cm thick carbon fiber composite test pieces using electron beam evaporation through a shadow mask to form parallel plate capacitors. Figure 2a shows the electrodes on either side of the sample which are 0.7 and 1.0 cm in diameter; different sizes are chosen so as to eliminate alignment errors, and the smaller diameter is the effective electrode diameter. The sample is mounted into an Agilent 16453A test fixture (Figure 2b), and reflection coefficient and phase are measured. Over most of the frequency range the reflection coefficient is close to 1 and reflection phase is near 180 degrees, indicative that the sample is electrically conductive and that a series resistor/capacitor model is appropriate [7]. Sample resistance and reactance were extracted



(a) (b)

Figure 2. (a) 16-ply carbon fiber composite material samples with gold electrodes; (b) sample mounted in test fixture for RF measurements.

from the reflection measurements. A key aspect of the measurement technique relevant to the RFMG application is that the electric field is primarily oriented in the out-of-plane direction, corresponding to the highest resistivity expected for these samples, and thus the parameter expected to limit the RFMG cavity Q values.

The measured resistance and reactance values as a function of frequency are attributed primarily to material properties, but the device geometry also has a role. Figure 3 shows that the minimum resistance = 1.2 Ω is observed at ≈ 500 MHz, which corresponds to the self-resonant frequency where the reactance = 0 ohms. At lower frequencies the reactance is negative, indicative of a capacitive reactance, and at higher frequencies the reactance is positive and thus inductive. This behavior is modeled using a series resistance/capacitor model. The goal of this analysis is to discern the resistive component of impedance of the carbon fiber composite panel. Although there is a reactive component, it is dependent on electrode size and not directly relevant to understanding if a fluid container constructed from carbon fiber composite materials would have adequately high Q values for use in RFMG applications. As an illustration, increasing the electrode size would increase capacitance and thus lower the self-resonant frequency of the test article, but the resistive component to impedance at the self-resonant frequency would not change. At 500 MHz the reactive component is negligible and only the sample resistance (=1.2 Ω) contributes to the overall impedance. The material resistivity (ρ) is obtained using equation 2, where R = sample resistance, A= electrode area, and L = sample thickness:

$$\rho = \frac{RA}{L} = \frac{(1.2\Omega)(0.38\ cm^2)}{0.096\ cm} = 4.8\ \Omega - cm \qquad \text{(at 500 MHz).} \qquad (2)$$

This value is consistent with the values from reference 5 discussed above. Using the RF impedance analyzer resistivity value measured at 500 MHz, equation (1) predicts a quality factor value of Q ~ 67 for a 2 m diameter spherical tank, but this should be regarded as a lower bound since the more relevant in-plane resistivity is expected to be significantly lower.

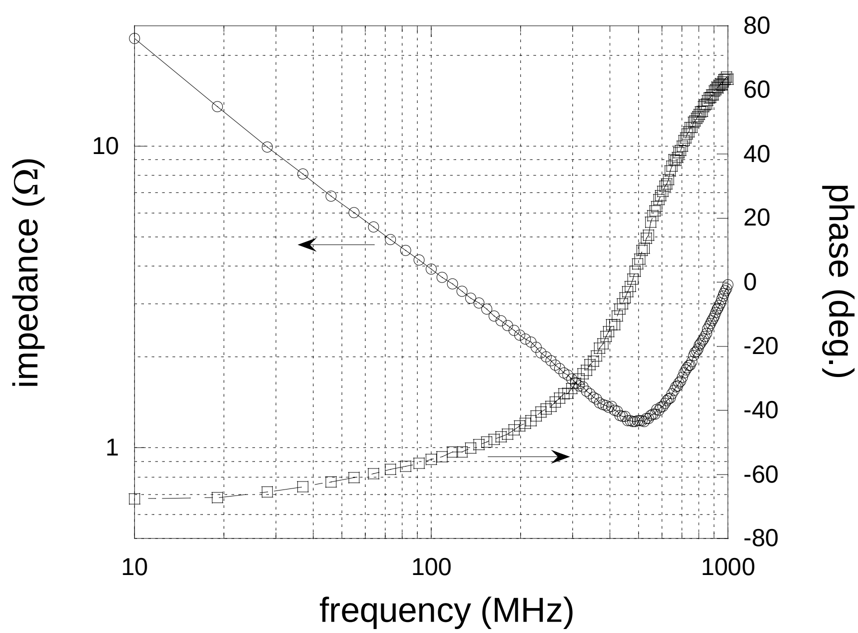


Figure 3. Impedance and phase as a function of frequency, from 10 – 1000 MHz. Minimum impedance (1.2 Ω) observed at ≈ 500 MHz. Phase = 0° at 500 MHz indicates negligible capacitive or inductive contributions to impedance, and measured impedance only reflects the resistive component to impedance.

WAVEGUIDE MEASUREMENTS

Waveguide reflection and transmission measurements were measured by inserting the graphite-epoxy-composite panels into a WR430 rectangular waveguide (10.92 cm x 5.46 cm inside dimensions) as shown in Figure 4, and measuring the reflected and transmitted signals using an Agilent E8361A performance network analyzer. The signal propagates in the TE10 mode, so the electric field is oriented perpendicular to the propagation direction, and parallel to the narrow face of the waveguide, which in this case is vertical. Data was acquired from 1.7 – 2.6 GHz. A time gate = 5 nanoseconds was applied to the measurement to reduce measurement errors caused by reflections at the input and output ports.

Figure 5 plots return and transmission loss as a function of frequency for four nominally identical carbon fiber composite panels. The reflection coefficient (Γ) is calculated using

$$\Gamma = 10^{\frac{-(return\ loss, dB)}{10}} \tag{3}$$

The return loss varies from 0.02 - 0.06 dB, corresponding to reflection coefficients of -0.995 and -0.984, respectively. Γ is negative because the panels present a conductive load to the signal. Treating the panels as a load with impedance Z_L, the load impedance is calculated by first rearranging the equation relating reflection Γ, Z_L, and the characteristic impedance of the waveguide (Z_0) in terms of Z_L: $\Gamma = (Z_L - Z_0)/(Z_L + Z_0)$ which is rearranged to give the load impedance as $Z_L = Z_0(\Gamma+1)/(1-\Gamma)$. Using the free-space impedance $Z_0 = 377\Omega$, Z_L ranges from 0.95 - 2.65Ω. The good reflectivity of the composite samples also suggested that a tank constructed from such a material would support RF tank modes.

(a) (b)

Figure 4. Test bed to measure reflectivity of 16-ply carbon fiber composite material. (a) Photograph showing WR430 waveguide with SMA connections to network analyzer; and (b) center section of waveguide, with carbon fiber composite inserted at center for reflection and transmission measurements.

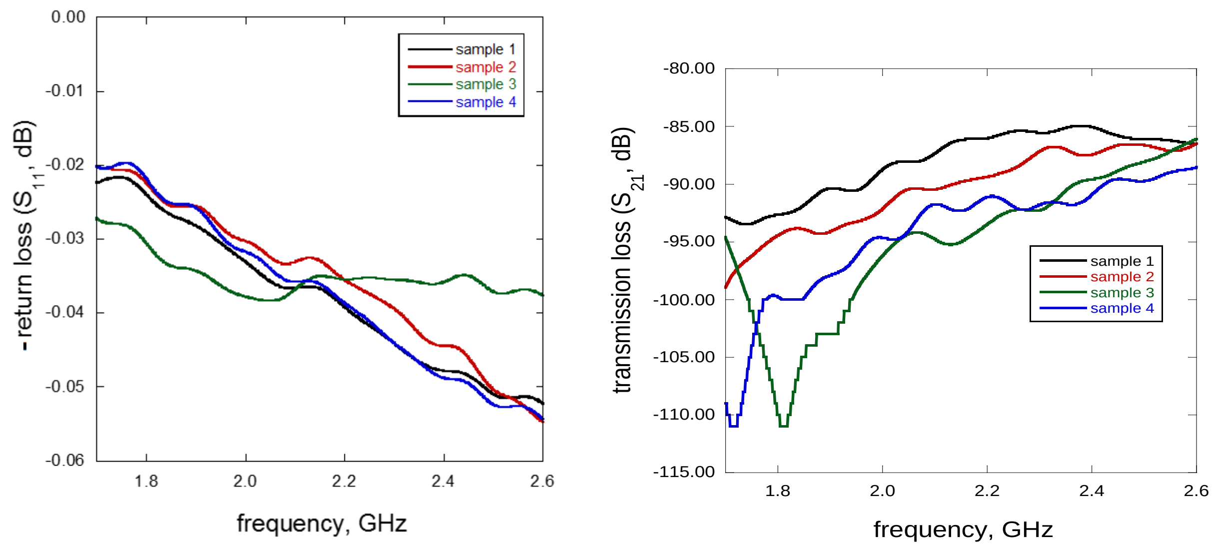


Figure 5. Waveguide measurements of s-parameter amplitudes S11 (left) and S21 (right) as a function of frequency from 1.7 – 2.6 GHz with a composite samples inserted in the waveguide. The four samples are nominally identical 16-ply carbon fiber composite.

<u>RF MODAL AND EMI MEASUREMENTS FROM A COMPOSITE CUBE</u>

Six panels of 8552/IM7 graphite-epoxy composite, each 0.91m square, were used to construct a composite box for preliminary RF mode testing and EMI characterization. The panels were fastened along the edges to 0.9m long aluminum angle sections to form a composite cube box. For EMI radiated emissions testing, copper tape was applied along the edge seams to help eliminate any spurious RF field leakage. In order to generate and detect RF modes in the cube, a 10 cm long monopole antenna with a 5 cm long coax lead-in was mounted on the center of one face using a non-isolated TNC bulkhead passthough connector. Reflection measurements from the antenna yielded spectra with good resonant modes at the expected frequencies, as shown in Figure 6. One of the predicted cubic box modes near 370 MHz was not excited by this antenna. The quality factor of the three modes shown in Figure 6 range from 100 < Q < 200, which, as expected, is better than the calculated value based on the RF impedance analyzer measurements. It should be noted that since the cubic box modes are degenerate, the mode near 400 MHz may contain unresolved, overlapping modes which would artificially lower the measured Q of that mode (Q ~ 100).

Based on the 5 mm skin depth calculated from the out-of-plane resistivity measurements, and also based on the waveguide transmission measurements, one expects some of the RF field to penetrate the composite box (or tank) walls when exciting an RF mode. To quantify this, we tested the composite box inside the 24’ x 32’ reflective EMI test chamber at NASA Glenn Research Center, where we measured the radiated electric field strength while exciting the box mode at 230 MHz with a 0 dBm RF source signal. Figure 7 shows the resulting radiated electric field strength measurement. For comparison, a nearly identical aluminum box was also tested and the radiated electric fields from the aluminum box were generally about 20 dB lower than from the composite box. The possibility of radiated electric fields from the coax cable or RF passthrough on the box contributing to the measurements was discounted after replacing the box antenna with a shielded open load and measuring negligible radiated field levels.

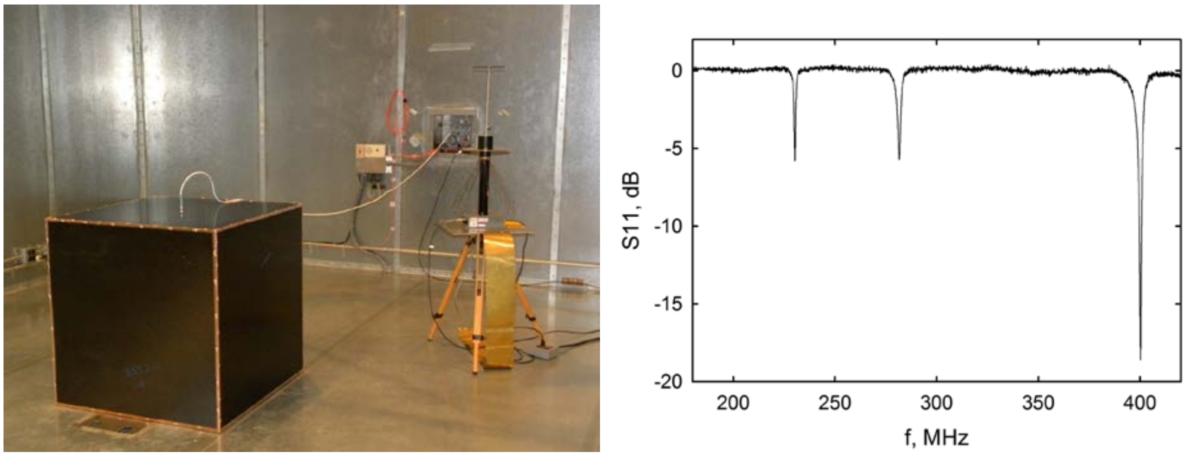


Figure 6. Photo of the composite box used for RF mode and EMI testing and (right) a sample RF spectrum from the composite box.

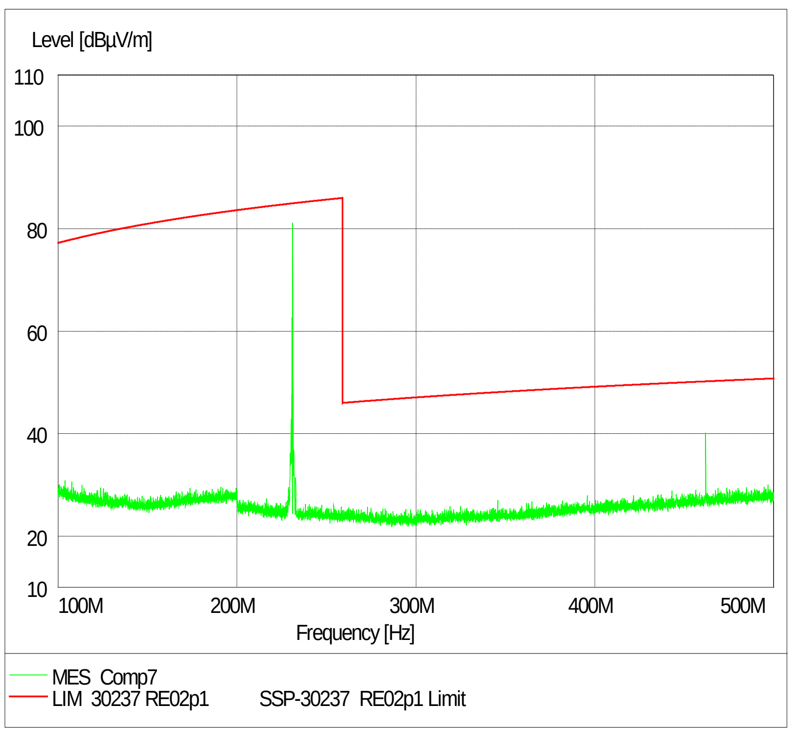


Figure 7. EMI test results from the composite box. A resonant mode of the box was excited at 230 MHz during the measurement. The green line shows the measured field strength at the EMI lab antenna, the red line is a Space Station radiated emissions limit line for comparison (from SSP 30237 Rev. F)

RF MODAL MEASUREMENTS FROM A COMPOSITE TANK

In 2013, Boeing delivered a 2.4 m diameter composite tank to NASA's Marshall Space Flight Center for cryogenic testing [8]. Upon completion of those tests, we measured the tank RF mode spectrum using an RF reflectometer with -10 dBm source signal and either of two antennas mounted to an aluminum T-bar mast which was attached to a circular aluminum plate, as shown in Figure 8. The dipole antenna was trimmed to a 30cm tip-to-tip length to characterize the lowest tank modes, and the 5 cm diameter loop antenna was used to measure tank modes at higher frequencies (data not shown). The plate and antenna mast assembly was press-fitted to the open bottom port of the composite tank using several floor jacks around the perimeter of the plate.

A sample tank spectrum acquired from the dipole antenna is shown in Figure 8, and shows excellent modal response. Using data from eight well isolated modes in the range 100 – 800 MHz that displayed good coupling to the tank, the measured Q values ranged from $440 < Q < 2,800$ with an average value of $Q \sim 1,500$. Q-factor values extracted from the loop antenna data are consistent with that from the dipole antenna. Larger tanks, with a higher volume to surface ratio, are expected to have even higher Q factors.

It is interesting to calculate an effective resistivity of the tank walls based on the average Q-factor measurement. From (1), using a geometrical factor ~ 2 (based on ref. 4) and a volume to surface ratio of 0.4, the inferred resistivity value is 0.06 ohm-cm at 500 MHz, which is somewhat higher that the in-plane resistivity value quoted in the introduction. It is possible that a bolted-lid configuration would provide better electrical contact between the lid and tank, and could result in even higher Q values. Cooling a graphite-epoxy composite tank down to 20 K is not expected to significantly change the cavity Q since resistivity measurements of similar composites show little change from 20 K to 293 K [9].

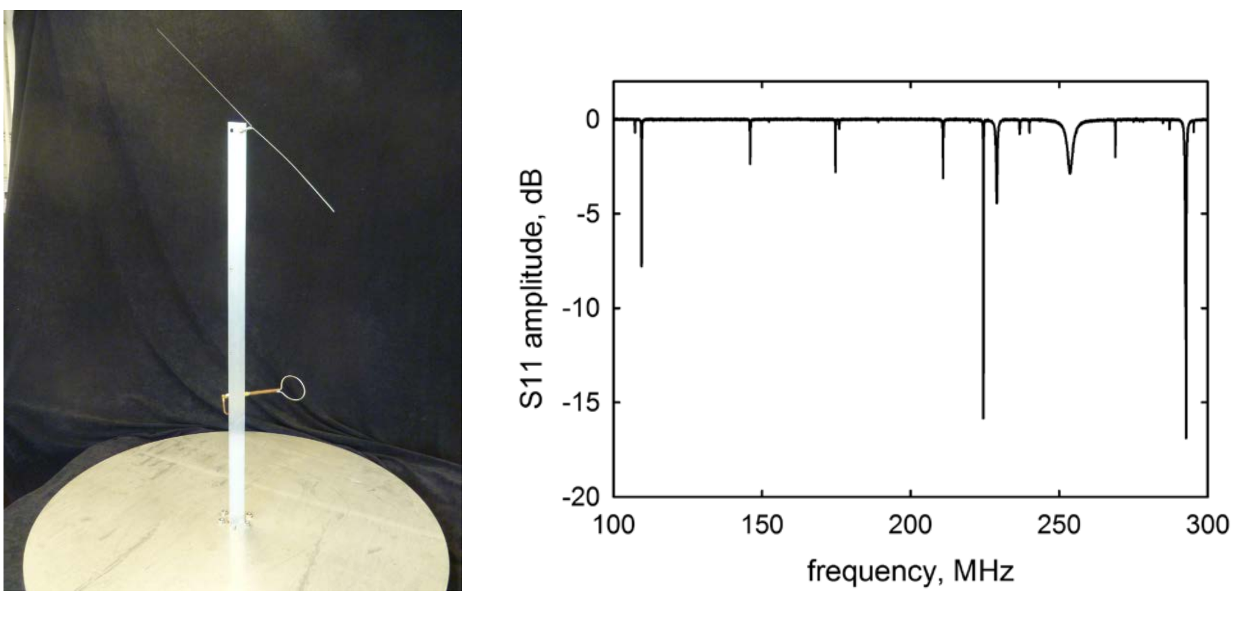


Figure 8. Photo (left) of the antenna mast assembly used to measure the composite tank RF spectrum (right). The tank spectrum was measured with the dipole antenna trimmed to a 30 cm length.

SUMMARY AND CONCLUSIONS

We have shown that the Radio Frequency Mass Gauge, which senses the electromagnetic modes of a tank to infer propellant quantity, is compatible with graphite-epoxy composite tanks. RF modal measurements from a 2.4 m diameter composite tank show an excellent mode response with Q values around 1,500. Larger composite tanks are expected to have somewhat higher Q values since the Q roughly scales with the tank diameter. Compared to similar sized aluminum tanks, where the Q factor can be 10^5 or higher, the composite tanks offer the benefit of being relatively high-Q, but not so high as to make modal measurements difficult.

ACKNOWLEDGMENTS

This work was supported by NASA's Space Technology Mission Directorate, through the Cryogenic Fluid Management and Evolvable Cryogenics projects. We wish to thank M. Asipauskas, S. Metzger, J. Wagner, and M. Herlacher for providing computational, mechanical, and measurement support, and especially thank Justin Jackson at NASA MSFC for helping to enable the RF measurements on the composite tank.

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